NASA SP-99

Significant Achievements in

Planetology 1958-1964

Scientific and Technical Information Division 1966
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

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WASHINGTON, D.C., 20402 - PRICE 45 CENTS

Foreword

THIS VOLUME IS ONE OF A SERIES which summarize the progress made during the period 1958 through 1964 in discipline areas covered by the Space Science and Applications Program of the United States. In this way, the contribution made by the National Aeronautics and Space Administration is highlighted against the background of overall progress in each discipline. Succeeding issues will document the results from later years.

The initial issue of this series appears in 10 volumes (NASA Special Publications 91 to 100) which describe the achievements in the following areas: Astronomy, Bioscience, Communications and Navigation, Geodesy, Ionospheres and Radio Physics, Meteorology, Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics.

Although we do not here attempt to name those who have contributed to our program during these first 6 years, both in the experimental and theoretical research and in the analysis, compilation, and reporting of results, nevertheless we wish to acknowledge all the contributions to a very fruitful program in which this country may take justifiable pride.

HOMER E. NEWELL
Associate Administrator for
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Preface

PLANETOLOGY AS DEFINED HERE is the science which treats of the condensed matter of the solar system excluding the Sun. Thus, planetology is concerned with the genesis, distribution, and composition of matter in the planets and their satellites, the comets and asteroids, and other solid materials in the solar system. In a sense, planetology embraces such fields as geology, geography, petrography, mineralogy, seismology, and vulcanology and extends their scope of interest beyond the Earth to include all the condensed material of our solar system.

Although the Earth is part of the subject matter of planetology, it is already receiving much attention. This report will limit consideration of research on the Earth to those studies that are undertaken to shed light on the planetology of extraterrestrial objects.

Clearly, for any planet that has an atmosphere, the planetologist must be concerned with the interaction between atmosphere and planetary surface. Similarly, the planetologist is concerned with the interactions of the flux of particles and radiations characteristic of interplanetary environment with satellites, planets, meteors, and so forth.

At present, the direct sources of planetology data are terrestrial observers and unmanned space probes. In the near future manned satellites and manned space probes will become additional and important sources of data about the Moon and planets.

Indirect sources of information on planetology range from experiments on materials under simulated planetary or lunar conditions to observations of those geological phenomena on Earth that are believed to be similar to planetary or lunar phenomena. They also include theoretical studies of models and related experimental data.

Most knowledge of planetology to date has been derived from Earth-based observations. This is partly because, as noted before, the initial space exploration has been undertaken mainly to develop the capability of making extraterrestrial voyages and to secure information on space environment. In addition—and this is an important consideration—Earth-based observations are emphasized for reasons of economy in human and material resources; there is no need to use a space probe to obtain data that can be obtained by observers on Earth.

The body of this report was prepared by James G. Beckerley, associated with the Massachusetts Institute of Technology, and the Preface was written by Urner Liddel, Lunar and Planetary Programs, Office of Space Science and Applications, NASA.

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chapter 1

Introduction

PLANETOLOGY, the study of the condensed material of the solar system, is at least as old as our historical records. Man's innate curiosity has led to the accumulation of a sizable body of knowledge in the general field of geology. This report discusses those studies of the Earth relating to extra-terrestrial bodies and describes the results obtained from the two spacecraft probes—Mariner II, which flew by Venus, and Ranger VII, which photographed the Moon at close range. Approximately 20 percent of the research reported, on the basis of papers cited, is supported by NASA. Obviously, the cost of Mariner and Ranger in funds is many times greater than the cost of all other research combined.

This report is organized according to the type of observation: Earth-based measurements of electromagnetic radiation from the Moon and planets, simulation and terrestrial-counterpart studies, investigations of chemical-mineralogical composition and genesis, and spacecraft observations. A final section discusses the instrumentation being developed to improve and extend observations from Earth and from space probes and vehicles.

It is not possible to review many of the large number of qualitative (and speculative) reports published from 1958 to 1964. Their omission is not intended to imply that such reports are without merit; certainly each "hard" fact concerning the Moon and planets merits extrapolation and speculation.

HIGHLIGHTS

Results from the Mariner II mission showed that if Venus has a magnetic field, it is no greater than one-tenth that of the Earth. The temperature across the outer cloud surface is essentially uniform, whether or not it is sunlit; however, one point on the cloud surface was found to be appreciably colder than the rest. Extrapolation of Mariner II measurements indicates that the surface temperature could be as high as 500° C (obviously a landing capsule is required to determine the true surface temperature). These temperature measurements made by Mariner II were confirmed and elaborated on by ground-based observations made with the Mount Palomar telescope during unusually good seeing conditions. The Mariner II flight also indicated that there were extremely few dust particles between Earth and Venus. Careful radar measurements by the Jet Propulsion Laboratory's radar telescopes at Goldstone have determined that Venus rotates very slowly in a direction opposite to that of all the other planets.

Telescopic pictures of the Moon have been collected and published in a single atlas, so that the entire visible portion of the Moon is available for reference. By a novel technique, G. P. Kuiper has been able to make "rectified" pictures of the lunar surface, showing how the edges of the Moon would look if one were able to view them from a vertical direction. Careful photometric studies of the lunar surface have made possible "geological" maps, which indicate variations in the surface material. These maps have been, and will continue to be, useful in selecting sites for Ranger and Surveyor missions.

Radar investigation of the lunar surface shows it to be smooth to radiations roughly 1 yard in wavelength. As the wavelength is decreased, the lunar surface becomes rougher and rougher, approaching the roughness observed by visible light. Some of these radar measurements indicate that the lunar surface is spongy. Attempts have been made in the laboratory to duplicate the visible-light characteristics of the lunar surface, and this has been done with very light, spongy material.

Telescopes have been used to make temperature measurements of the lunar surface after "sundown." Many areas have been observed to cool down much more slowly than the general lunar surface, which indicates that these areas are markedly different in composition from the general lunar surface.

Although Sir William Herschel reported seeing red spots or clouds on the lunar surface in the first decade of the 19th century, few additional reports, if any, were received until 1957 when Kozyrev reported seeing red clouds in the crater Alphonsus. In October 1963, additional sightings of red clouds were made, this time near the crater Aristarchus. Further sightings in that same area were made in November and December 1963 and in June 1964. Although various theories have been developed on the origin of these phenomena, no consensus is held by the astronomers. However, these observations indicate at least that the lunar surface is not completely inactive.

The successful mission of Ranger VII provided photographs of the Moon at some thousand times greater resolution than those obtained from Earth-based telescopes. The full interpretation of these pictures will require a long time, and there is still disagreement on interpretation. It is apparent, however, that craters are the dominant topographic feature of the Mare Cognitum surface at all scales down to less than 1 meter. The distribution of the craters is not uniform but more abundant in the "rays" than in the intervening area. It has been estimated that some 50 percent of a ray area is occupied by craters. In the last full-scan photograph before impact, small craters may be seen within larger ones.

Another observation from Ranger VII photographs is the scarcity of small surface bumps or isolated protuberances. A measurement of slopes in the last partial-scan photograph shows that in over 90 percent of the area, the slopes were less than 15°

PLANETOLOGY TODAY

In the preface to a recent edition of his book, *Earth, Moon, and Planets,* F. L. Whipple of the Smithsonian Astrophysical Observatory wrote that he was "struck, not by the increase of knowledge concerning the planets that we have gained in two decades, but rather by the greater amount that we may expect to gain in a far shorter time" (ref. 1).

This statement reflects accurately the situation in planetology at the present time. Knowledge of the planets and the Moon has steadily been accumulated in Earth-based laboratories and observatories, a tantalizing few measurements have been relayed to Earth from unmanned space probes, and there is a firm optimism over future progress.

Almost all the dozens of satellites and space probes sent into orbit during the past 6 years were sent into space for purposes other than that of securing data concerning the Moon and planets. In fact, very few to date have made contributions to planetology, but the contributions have been significant: a remarkably clear view of the details of the Moon's "face"; a preliminary glimpse of the hidden part of the lunar surface; measurements of infrared and microwave radiation from Venus, observed from a distance of about 22 000 miles; and a measurement of the magnetic field at that same distance.

The information about planets that has been derived from space probes is still not very extensive, simply because the initial goals have been to put space vehicles into accurate, predetermined orbits and to accumulate data on the space environment. The first of these goals has required enormous engineering efforts, and the second has engaged a considerable body of astronomers and physicists. Both goals, although not directly related to planetological research, must be reached before the planetologist can undertake his extraterrestrial research.

Most current research in planetology is in Earth-based facilities. Many astronomical observatories are gathering data about the Moon and about the planets and their satellites by using both old and new instruments. Radio-astronomers are examining the radiations that planets emit, as well as their response to radiations sent from Earth. Geologists, mineralogists, and chemists are examining extraterrestrial materials—tektites, meteorites, and meteoritic dust—found on Earth; and physical-chemical experiments are being performed to discover the conditions and processes involved in creating these materials. Scientists in laboratories, now able to simulate lunar and planetary environments, are investigating the properties of relevant materials in these environments. Field geologists are investigating in detail meteoritic and volcanic craters on Earth to shed light on the origins of apparently similar lunar features.

PROBLEMS FACING THE PLANETOLOGIST

This report summarizes the achievements in planetology during the first 6 years of the space age. The increased interest in the Moon and planets has persuaded many scientists and engineers to engage in planetology research—geologists who now examine terrestrial craters with a "lunar bias"; electronics engineers who now consider effects of space environment along with the effects of other unusual conditions on terrestrial devices; and theoretical physicists who are stimulated to study the origin of the solar system as well as other problems of cosmogony.

Among the questions the planetologist asks about the Moon are: What is the nature of the lunar surface? Will it support the astronaut and his instruments? What is the chemical and physical composition of the lunar surface? Does the detailed physical character of the lunar landscape confirm or contradict theories of meteoritic impact and vulcanism? What is in the shadows of lunar crevasses—ice, condensed gases, etc.? What is the composition of the material just under the lunar surface, and what is its temperature? Are there seismic disturbances on the Moon? Can the lunar interior be probed with seismic techniques? What is the precise shape of the Moon? Is there a tenuous heavy-gas atmosphere?

Similar questions have been asked about Mars, Venus, and Mercury, except that as the planets are more remote, the questions begin at a more elementary level. The topography of these planets is unknown. Mars is seen through its almost transparent atmosphere, but the surface of Venus is hidden. The surface of Mercury is visible, but its distance from the Earth and proximity to the Sun are obstacles to Earth-based observations. The planetologist would like data on basic phenomena, such as a more precise value of Venus' period of rotation, Mars' magnetic field, the composition and dynamics of the planetary atmospheres and interiors, the nature of the surfaces of the planets, and the processes that act on these surfaces to change them.

Some fundamental questions concerning the Moon will be answered soon, probably within a decade, but many questions about the planets may not be answered for decades. When it becomes possible to place the equivalent of a good astrophysical observatory outside the Earth's atmosphere—in a terrestrial or lunar satellite, or on the Moon or even on an asteroid—then the planetologist will be able to use his tools with greater effectiveness. He still will have to contend with various planetary atmospheres. Because of the relatively opaque atmosphere of Venus, research is likely in the near future to uncover more information on Mars and Mercury than on Venus.

APPLICATIONS OF THE RESULTS OF PLANETOLOGY RESEARCH

The primary motivation for research in planetology is the desire to learn more about the solar system. This knowledge can lead to an understanding of the origins and perhaps the destiny of the solar system. It can lead to an understanding of the physical and chemical behavior of materials in unusual environments, and even of life in "unearthly" surroundings.

A short-range objective of planetology research, if human beings are to visit the Moon or nearby planets, is to secure environmental information relevant to the safety of planetary explorers. For example, the exact nature of the atmosphere and surface of Mars must be known so that the first visitor can be equipped for survival. Even a landing on the Moon cannot be made until there is an unambiguous answer from planetology research as to the mechanical strength of the lunar surface. Most of these answers can be given only when the planetologist has more data from unmanned space probes.

To those who question the value of his research, the planetologist can affirm that while extending the boundaries of human knowledge is a worthy goal in itself, past experience has shown that every extension of knowledge leads to new devices, new materials, and new processes that can be used to enrich human experience.

chapter 2

Terrestrial Observations of Electromagnetic Radiations From the Moon and the Planets

MOST OF THE PLANETOLOGIST'S BASIC DATA are derived from observations of lunar and planetary electromagnetic radiations. The ultraviolet, visible, and near-infrared radiations from the lunar or planetary surface are reflected and scattered sunlight; the longer wavelength infrared and microwave radiations are emitted as a result of the surface or near-surface temperatures.

Almost 20 years ago the first radar echoes were obtained from the Moon (refs. 2 and 3). Improved techniques during the intervening period have given the planetologist another electromagnetic probe. Within the past few years it has also been found possible to "bounce" coherent light beams from the Moon. The value of this technique remains to be determined.

EFFECTS OF THE EARTH'S ATMOSPHERE

Unfortunately, the earthbound observer sees all extraterrestrial objects through the Earth's atmosphere. The same atmosphere that shields the Earth's surface from the lethal radiations of the Sun also screens out much information-bearing radiation from the planets. All radiation below the near ultraviolet is effectively absorbed by the Earth's atmosphere. Above this lower wavelength limit, there are three principal windows through which the earthbound observer can view extraterrestrial events (refs. 4–6).

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(1) *Near-ultraviolet and visible-radiation window*
Wavelength: 2900 to 7000 Å
Frequency: 1.03×10^9 to 0.43×10^9 Mc/sec

(2) *Infrared window*
Wavelength: 8 to 14 μ
Frequency: 3.8×10^7 to 2.1×10^7 Mc/sec

(3) *Microwave-to-decameter window*
Wavelength: 1 mm to $\lessapprox 100$m
Frequency: 300 000 to $\gtrapprox 3$ Mc/sec

The values listed are approximate. In fact, there are blind spots in each of the above windows; e.g., the O_2 and H_2O absorption bands in the 1- to 10-millimeter region. There are also some partial windows; e.g., in the 2- to 6-μ interval. The long-wavelength limit (100 meters) varies with the ionospheric transmission, which is a function of sunspot activity and other phenomena. The exact location of the observer is also an important factor in the atmospheric transmission, as a result of local variations in dust and water-vapor content.

Observations can be made between these windows, provided suitable corrections can be made for the effect of the Earth's atmospheric absorption. For example, it has been possible to determine the constitution of the Martian atmosphere by making observations at a time when Mars is near quadrature, the position where it has maximum motion toward or away from the Earth (refs. 7 and 8). Under these conditions the absorption spectrum of the Martian atmosphere is shifted with respect to that of the Earth by the Doppler effect. However, such measurements are difficult, and, wherever possible, observations are made through the atmospheric windows.

Most photometric, colorimetric, polarimetric, and visual observations are made through the first window. Through the second window, temperatures of planetary or lunar surfaces and atmospheres are determined. The shorter wavelength region of the third window (up to a few meters) can also be used for investigation of planetary and lunar temperatures. The longer wavelength region (from about 20 centimeters up) is the window through which the radioastronomer receives signals from planetary sources and through which radar echoes from lunar and planetary bodies are received.

In addition to absorbing and scattering radiation, the Earth's atmosphere can distort the image formed by a telescope. At any instant the image of a source can be distorted in shape and moved to a new position not necessarily in the same plane. The effect results from the variation in properties of that part of the atmosphere through which the light rays are transmitted. To reduce the effect, the observer seeks to locate his instruments where the atmosphere is relatively stable. As distortion of the image depends on variations along the path of the received beam of light, narrowing the aperture of the telescope (i.e., reducing the extent of the received beam) helps in some situations, but with a resulting loss of intensity and resolving power. An excellent review of the problems of observing and photographing through the Earth's atmosphere is given in reference 8.

In 1610, Galileo was able to discern objects separated by an angle of about 10 seconds. By 1680 this angle was reduced to about 1 second by the astronomer Cassini. Thus, in the first 70 years, the resolving power of telescopes was improved by a factor of 10. However, in the next 270 years, the improvement in resolving power was only by a factor of 4 or 5. The practical limits of resolution for present-day telescopes (for visible radiation) are in the range 0.4–0.2 second. This is to be contrasted with the theoretical limits of resolution set by diffraction effects: about 0.027 second for the 200-inch (508-centimeter) Mount Palomar telescope, or about 0.23 second for the

Pic du Midi 60-centimeter (23.6-inch) instrument. These latter values are for visible (5400Å) radiation; for longer wavelength radiations, the limit is proportionately larger.

The limits placed by the Earth's atmosphere on the resolving power of telescopes are significant barriers to the observation of planetary details. Because of the great distances to the planets, their angular diameters are small. Mercury has a maximum angular diameter of about 13 seconds, and when it is this large it is in an unfavorable position for observation. Venus, passing closer to Earth, has a maximum diameter of 64 seconds, but also when in an unfavorable position. The maximum angular diameters of the other planets are: Mars, 26 seconds; Saturn, 21 seconds; Jupiter, 49 seconds; Uranus, 4 seconds; Neptune, 2 seconds; and Pluto, 0.3 second. The Moon has such a large angular diameter, 1860 seconds, or about $\frac{1}{2}^\circ$, that atmospheric limitations are less significant until one becomes interested in lunar details of about 1 mile (1.6 kilometer) in extent (1 mile corresponds to about 1 second in arc).

Detection of long-wavelength radiation involves similar problems of resolution. For example, a 50-foot (1520-centimeter) receiving antenna for 3-centimeter (10 000 Mc/sec) radiation has a theoretical resolution of about 500 seconds in angle. This is many times the angular diameter of the planets. Consequently, the antenna will average the emission from the entire planetary surface. To secure data on microwave radiation from a selected part of a planetary surface requires an impractically large antenna; observations from space probes are almost mandatory. (In some cases, interferometry techniques can be used to identify radiation from specific areas.)

There have been no striking achievements during the past 6 years in surmounting the obstacles presented by the atmosphere. There has been an intensification of basic studies on atmospheric effects, and there have been refinements in photographic techniques. A. Dollfus has reviewed some of the techniques (e.g., preparation of composite photographs by superposition of more than 10 images taken in succession on one plate) used at the Pic du Midi Observatory in visual and photograph studies of the planets (ref. 9). These illustrate the ingenuity and painstaking care that are required to approach the limits of resolution.

LUNAR MAPPING

Details of the lunar surface have been studied for the past century, both visually and photographically. During the years 1958–1964 a number of lunar atlases were prepared. Although not one of the atlases approaches the precision of accepted standards for mapping the surface of the Earth, the new atlases do represent an important advance in lunar mapping. They provide a reliable framework within which to locate information derived from unmanned lunar probes and early manned lunar exploration. The fundamentals of lunar mapping are discussed in references 10 and 11. The various papers presented at the Fourteenth Symposium of the International Astronomical Union (December 1960) also review lunar mapping (ref. 12).

The *Photographic Lunar Atlas, published* in 1960 (ref. 13), includes 230 photographs, each 40 $\times$ 50 centimeters (15.7 $\times$ 19.7 inches), with approximate scale of 1:1 370 000 (lunar diameter=2.5 meters). In this atlas the lunar surface is divided into 44 areas, each being presented under at least 4 different solar illuminations.

The two-volume *Orthographic Atlas of the Moon,* published in 1960–62 (ref. 14), consists of 60 large-scale photographs with a superimposed orthographic grid (interval= 0.01 lunar radius). All regions that do not involve the Moon's limb areas are included in the 29 photographs of the first volume, while the limb regions are in the second volume. Selenographic positions can be interpolated from these maps with an accuracy of at least 0.001 lunar radius in central regions and 0.002 lunar radius in limb regions (ref. 15). Edition A of the atlas has just the orthographic grid; Edition B has a latitude-longitude grid overprinted in color.

Because of the curvature of the Moon's surface, use of these photographs in mapping is not entirely satisfactory, especially in the limb regions. In the *Rectified Lunar Atlas,* published in 1962 (ref. 16), the lunar surface, excluding the poles, was divided into 30 fields. To remove foreshortening of the limb, lunar photographs were projected on a 3-foot (91.44-centimeter) precision hemisphere of mat-white surface and rephotographed from a position normal to the surface (ref. 17). For each of the 30 fields, the atlas presents photographs rectified in this way for three illuminations (sunrise oblique, local noon, and sunset oblique). The scale is 1:4 000 000.

The most extensive relief-mapping effort, combining photography and visual observation, is being done at the Aeronautical Chart and Information Center (ACIC) of the U.S. Air Force, in cooperation with several universities and observatories (ref. 18). Initial work in the equatorial belt will result in a series of 28 topographic maps roughly 55×75 centimeters, 1:1 000 000 scale, covering the visible region of the Moon lying in the interval within $\pm 32°$ of the Equator. Over limited distances, positions of points on the lunar surface can be determined within 1 kilometer. Elevation differences are determined by a refined shadow-measuring technique. Relative heights of parts of a specific lunar feature are considered to be measured to a probable error of 100 meters, the probable error in elevation between widely separated features being about 10 times larger. Tens of thousands of photographs of the lunar surface are being used in this project.

Associated with these intensive topographic-mapping efforts have been a number of other lunar studies. A *Consolidated Catalog of Selenographic Positions,* published in 1962 (ref. 19), gives 4510 selenographic positions, including direction cosines and crater diameters. This work was based on the *Orthographic Atlas of the Moon* and the *Rectified Lunar Atlas.* Similarly, a careful survey of all lunar craters with diameters larger than 3.5 kilometers (2.2 miles) is being made and published in a series of papers, *The System of Lunar Craters* (refs. 20, 21). The second lunar quadrant was published in 1964. The designations, diameters, positions, central-peak data, and so forth, of over 2000 craters are being cataloged. A *Catalog of Lunar Craters* that gives selenographic coordinates of lunar craters down to 1 kilometer in diameter is being prepared for representative lunar areas (ref. 22). Several statistical studies of crater-size distribution are being made.

In addition to the compilation of atlases based on photographs, much effort has been expended on visual observation of the lunar surface. Because the resolution of visual observations is about three times that of photographs, more accurate determinations of crater-depth-diameter ratios, external and internal slopes, and the nature of central peaks can be made by visual observations at several illuminations. The general practice is to use available photographs as the base on which to add the visually observed details (ref. 23). During the past several years, drawings of the lunar-limb area based on extensive visual observation have been published (ref. 24).

Another aspect of the Moon that is of interest to the planetologist is the distribution of its mass, referred to by astrophysicists as the Moon's "figure." Nonuniformity in the lunar-mass distribution must be supported by internal strength if the Moon is not in hydrostatic equilibrium. This, in turn, has implications as to lunar constitution. Through visual and photographic observation of the Moon, it is possible to determine its motion (rotation, orbital motion, and libration). These observations and the basic laws of motion permit a calculation of ratios of moments of inertia of the Moon (about the lunar axis of rotation, about the Earth-Moon axis, and about the axis tangent to the lunar orbit). The ratios between these moments can be compared with ratios computed assuming the Moon to be in hydrostatic equilibrium and with ratios computed assuming a Moon of uniform density. Observations and calculations of this type made in the past several years show that the Moon, for its present rate of rotation, has a greater concentration of mass along the Earth-Moon axis than would be expected from tidal theory (ref. 25). Two interpretations of the data have been made: either this nonuniform mass distribution represents a frozen tidal wave (the Moon solidified when it was nearer the Earth than now), or it is attributable to some near-surface (in the outer 300 to 400 kilometer) inhomogeneities. Unfortunately, there are too many uncertainties in present observational data to resolve the question. Future work—for example, the tracking of lunar orbiters—should clarify the situation.

LUNAR-SURFACE GEOLOGY AND PHYSICAL PROPERTIES

In addition to knowing lunar topography, the planetologist would like to know the surface properties. For at least a century it has been realized that the Moon does not scatter and reflect sunlight as do materials common on the Earth's surface. The long-recognized lack of darkening of the lunar limb at full Moon is evidence that the lunar surface is very rough at optical dimensions. Photometric measurements of the radiance of many parts of the Moon's surface at various lunar phases have been made for more than 50 years. But during the past 6 years these data have been reexamined and extensive measurements made using new and refined techniques. Recent as well as earlier work on lunar photometry has been reviewed (ref. 26).

Of particular importance is the albedo, or reflectivity, of the lunar surface. The normal albedo is the radiance of the lunar surface at the sub-Earth point—the center of the full Moon. Because the radiance at full Moon is nearly independent of the angle at which the surface is observed, for a given angle of illumination, the normal albedo of individual lunar formations is essentially their radiance near full Moon. Albedos for selected points on the lunar surface have been measured and cataloged for many years. These values have been reexamined and extended during the past 6 years; for example, see the discussion on page 236 of reference 26. In addition, as noted later in this report, attempts have been made to match these data with simulated lunar materials and surfaces. The lunar-albedo values vary from about 0.05 to 0.18, with an average value of 0.07. Correlation with lunar features confirms that the relative variations must correspond to differences in surface materials.

The U.S. Geological Survey is using the atlas of lunar topographic relief maps (being prepared by ACIC) as a base on which to prepare lunar geological maps. Five basic stratigraphic systems of progressively greater age have been recognized to date. These maps are based on albedo value, color, polarization, location, and structure, and show geologic features, such as folds, faults, and fault trends (ref. 27). When completed, these maps will constitute a compilation of geological features of the Moon insofar as they can be deduced from Earth-based observations. They will provide a basis for extrapolating to other lunar areas the localized geology determined from a spacecraft landing.

Prior to completion of the lunar topographic and photogeologic mapping, the U.S. Geological Survey has compiled a *Generalized Photogeologic Map of the Moon* and a *Physical Divisions of the Moon,* using a photomosaic in orthographic projection at a scale of approximately 1:3 800 000 (ref. 28).

During the years 1958–1964 there has been a renewed interest in the polarization of lunar radiation, particularly its wavelength dependence. Recent data in the infrared (0.32 to 1.0 μ) show that polarization varies roughly inversely with wavelength (ref. 29). Although polarization measurements have been made for over a century, interpretation of the results still is uncertain.

Another approach to identifying the properties of the lunar surface is to observe the "radio albedo"; i.e., the scattering and reflection of radar pulses. Analysis of radar echoes (wavelengths of 3.6 and 68 centimeters) in recent experiments shows that most of the lunar surface is smooth and undulating, with gradients of about 1 in 10 for points separated by about 70 centimeters and of about 1 in 7 for points separated by about 3.6 centimeters (refs. 30 and 31). Only about 8 percent of the surface is covered with structures whose size approximates a wavelength of 68 centimeters, while about 14 percent of the surface contains irregularities comparable to a wavelength of 3.6 centimeters. The radar echoes also yield information on the electromagnetic constants of the lunar surface (ref. 32); these data are discussed in connection with laboratory simulation studies.

The emission of infrared and microwave radiation from the Moon depends on the lunar-surface temperature. The variation with phase of the Moon of infrared- and microwave-radiation emission has been investigated during the past 6 years using improved radiometric techniques. For 10-centimeter radiation, the apparent lunar temperature at the center of the Moon's disk is constant: 232° K±4.5° K (ref. 33). On the other hand, for 4-millimeter radiation the apparent lunar temperature varies with lunar phase, and fluctuates about 70° K above and below 230° K (ref. 37). At intermediate wavelengths (3.2, 2.3, and 1.25 centimeters), the temperature fluctuation is less (refs. 34–36). (Measurements made before 1961 have been summarized in ref. 38). The relation between lunar phase and fluctuation of the radio temperature is such that the longer the wavelength, the more the radio temperature lags behind the lunar phase. Thus, for 1.25-centimeter radiation the radio temperature is maximum after full Moon (about halfway between full Moon and third quarter; see p. 45 of ref. 6), while for 4-millimeter radiation the temperature reaches a maximum very soon after full Moon.

The significance of these data is readily seen. The longer wavelength radiation is emitted from farther below the lunar surface (about 1 meter down), and these deeper layers stay relatively constant in temperature during the lunar day and night. The shorter wavelength radiation is emitted by the surface layers, which experience a rise and fall in temperature as the lunar day and night come and go.

The periodic heating and cooling of the lunar surface, as revealed by infrared and microwave temperature measurements, provides quantitative information on the thermal properties of the lunar surface. This will be discussed later in connection with laboratory simulation research.

Lunar eclipses provide excellent conditions for observing lunar temperatures. Observations before, after, and during a lunar eclipse reveal local inhomogeneities in the heating and cooling rates that are indicative, for example, of denser rock patches in certain areas. During the December 18, 1964, lunar eclipse, extensive infrared scanning of the Moon (200 transit lines to cover the entire disk, a 17-minute procedure) showed 400 to 800 local "hot spots" (R. Shorthill, Boeing Research Laboratories, as reported in the New York Times by W. Sullivan, Jan. 9, 1965, p. 27). For example, the Tycho crater was found to be 50° K higher than the neighboring regions. These results confirm earlier findings, where a much smaller number of such thermal anomalies were observed (refs. 39 and 40). Correlation of these more recent measurements with specific features on the Moon's surface should add to the knowledge of lunar geology. In earlier work there appeared to be an association between some of the hot spots and large, younger craters.

During the past 6 years, several observers have reported transient phenomena on the lunar surface. In November 1958 an apparent emission of gases (between ½ and 2 hours in duration) from the crater Alphonsus was seen. A spectrogram taken during this occurrence was interpreted as showing that solar radiation had caused a gas containing C_2 molecules to fluoresce (refs. 41 and 42). Other observations of similar events in Alphonsus (1937, 1956, 1959) tend to support the view that there is active lunar vulcanism (ref. 43). These and other recent observations have stimulated review of past records (back to about 1830) to find what other changes or transient activities have been noted (refs. 44 and 45). From these reviews and more recent reports, it has been learned that anomalous and temporary changes have been observed in the appearance of the Agarun promontory and in the craters Aristarchus, Linné, Plato, and Tycho. While the validity of some of these observations has been questioned, they might influence the priority of lunar sites to be explored at an early date. If volcanoes or lunar hot springs, fumaroles, or other thermal anomalies are active, these will be of substantial interest not only to the planetologist but to lunar astronauts. Such regions may be exploited as heat and power sources, or even "mined," if there is useful material involved.

Although the interpretations of reports of "events" on the lunar surface are certainly varied—and controversial—these reports have stimulated an increase in the number of systematic, extended-period visual and photographic observations (ref. 45). These efforts, it is hoped, will provide information on rare lunar events, assuming that such events produce visible effects. Of course, much more data on local phenomena will become available when Lunar Orbiters and Explorers are operational.

Before concluding the review of the Earth-based observations of lunar radiation, it should be noted that such observations provide information on the lunar atmosphere, or its absence. It has long been known that the Moon has little or no atmosphere. No refraction of light is visible at the Moon's limb during the occultation of a star or during a solar eclipse. Until about 10 years ago, the upper limit of the surface density of the lunar atmosphere was estimated (from occultation data) to be about 10^{-9} of the sea-level atmospheric density on Earth. Seven years ago, observations of the occultation of radio stars reduced this upper limit (ref. 46). The present view is that the atmospheric pressure at the lunar surface is less than 10^{-12} torr. Some studies of the interaction of the solar wind with the lunar surface have led to the conclusion that there may be an atmosphere of about 10^5 hydrogen atoms/cm^3 at the lunar surface (ref. 47). These same studies indicate that the solar wind and the absence of a lunar magnetic field result in the sweeping off of any heavy gases that might accumulate near the lunar surface, as a consequence, for example, of lunar outgassing.

OBSERVATIONS OF RADIATIONS FROM VENUS

Venus has an atmosphere that effectively obscures its surface from the Earth-based observer. Visual and photographic examination reveal some apparent structure in the planetary disk. However, the markings are not permanent and seem to be variations in the Venusian atmosphere (p. 551 of ref. 9).

Recent observations of infrared emission (in the 8- to 13-μ region) confirm earlier (1953) temperature determinations and the near equality of infrared temperatures of sunlit and dark hemispheres. The infrared temperatures are all within a few degrees of —38° C (p. 455 of ref. 38). A review of the infrared data prior to 1960 is given in reference 48.

Significant new information has been obtained during the past 6 years from measurements of microwave temperatures. For 3- to 21-centimeter radiations, the apparent temperature is 350° C. For radiation below 2 centimeters in wavelength, the temperature decreases until it reaches about 117° C for 4-millimeter radiation (pp. 52–57 of ref. 6). (Other values reported in recent reports are: 137° C $\begin{Bmatrix} +30^\circ \text{ C} \\ -20^\circ \text{ C} \end{Bmatrix}$ for 8.6-millimeter radiation (ref. 48); 77° C $\begin{Bmatrix} +50^\circ \text{ C} \\ -20^\circ \text{ C} \end{Bmatrix}$ for 4.3-millimeter radiation (ref. 49).) This gradient in temperature, when taken with earlier infrared-temperature (—38° C) and optical-temperature (12° C) measurements, has been interpreted as indicative of an increase in temperature as Venus' surface is approached. The long-wavelength temperature (350° C) is probably characteristic of the surface temperature; the shorter (4-millimeter) wavelength radiations from the surface are unable to penetrate the thick cloud layer, and the observed temperature (117° C) is therefore the temperature at some distance above the surface. The optical-radiation temperature (12° C) is characteristic of the top of the cloud cover, while the infrared (8 to 13 μ) temperature (—38° C) is the temperature some distance above the cloud cover. The fact that the infrared radiation shows a limb-darkening effect tends to confirm this latter deduction, as it indicates that the infrared emission takes place in a region where the temperature decreases with the height (p. 455 of ref. 50).

Since recent temperature measurements at 3.15 centimeters show a relationship to solar phase, it is now believed that the surface of the sunlit hemisphere is some 145° C higher than the surface temperature of the dark hemisphere. The near equality of the infrared temperature in sunlit and dark hemispheres is interpreted as showing that there is very little horizontal gradient in temperature in the upper atmosphere of Venus. Effective mechanisms must exist for circumferential transport of heat in the upper atmosphere.

The composition of Venus' atmosphere is of considerable interest to the planetologist, as it can be expected to provide clues to the surface conditions. In a balloon ascent in 1959 (above the water vapor of the Earth's atmosphere), spectrometric measurements indicated that the water-vapor content above the Venus cloud level was equivalent to a 19-μ-thick layer of water (ref. 51). It is generally believed that Venus' atmosphere has water vapor, but the amount and vertical distribution have not been determined. In a recent study of the infrared-absorption spectra (1 to 2.5 μ), all 40 absorption bands found were attributable to CO_2; none fitted the absorption spectrum of ice crystals (ref. 52). The basic difficulty seems to be that the cloud cover is so opaque to visible and infrared radiations that the escaping radiation does not lend itself to analysis—it is all millimeter- and longer-wavelength radiation. The entrapment of infrared radiation accounts for the high surface temperature and is basically a "greenhouse" mechanism.

In 1961 radar (12- and 68-centimeter radiation) reflections from Venus were measured (refs. 53–57). The echo pulse shape has been interpreted as indicating a surface smoother (in dimensions of radar wavelength) than that of the Moon. From the experimental value of the radar cross section, it has been deduced that the dielectric constant of Venus' surface is about that of quartz, indicative of a rock surface (ref. 58). The radar spectrum has been analyzed to see whether the period of rotation of Venus can be measured (refs. 57 and 58). Studies of Venus during the 1962 conjunction indicated a retrograde rotation of the planet, with a period of about 266 days (ref. 59). Improved radar observations made during the 1964 conjunction verified the retrograde rotation and led to a better defined period of 249±6 days (ref. 60).

OBSERVATIONS OF RADIATIONS FROM MARS

The most notable achievement during the past 6 years in securing data on Mars is the substantial improvement in knowledge of the Martian atmosphere. Prior to 1963, visual polarization measurements indicated the atmospheric surface pressure to be about 90 millibars (ref. 61). Infrared spectra (0.8 to 2.5 μ) of the Martian atmosphere taken with the Mount Wilson 100-inch telescope (ref. 8) and with the 82-inch telescope of the McDonald Observatory (ref. 7) in 1963 indicate that the surface pressure is only 17±3 millibars. From the same spectra, the Martian atmospheric composition, in percent by volume, was determined as: N_2, 85; CO_2, 14; Ar, 1; with a small concentration of H_2O (1 cm-atm). (See refs. 62 and 63.) Upper limits for a number of other constituents were established (refs. 64 and 65). The finding that the surface atmospheric pressure is low is of great significance in planning a Martian landing. The composition of the atmosphere is of value in trying to deduce the nature of the surface.

Measurements of the 3.15-centimeter radio emission at Mars during the past 6 years gave values for the apparent blackbody disk temperatures of 218±50° K and 211±20° K (refs. 66 and 67). Earlier (1924–32) values derived from infrared data had given appreciably higher values, 273° to 300° K (see summary on p. 426 of ref. 5), indicating that the 3.15-centimeter radio temperature is that beneath the planetary surface.

In 1963 the first radar contact (2388 Mc/sec, or 12.55-centimeter radiation) was made with Mars (ref. 68). The radar echo indicated a radar reflectivity intermediate between that of Venus and the Moon. Moreover, it was found that the roughness of the reflecting portion of the surface of Mars varied as the planet turned on its axis.

OBSERVATIONS OF RADIATIONS FROM MERCURY

Observations during the past 6 years have not added greatly to the knowledge of Mercury. Prior data show that the photometric properties of Mercury's surface are similar to those of the Moon (ref. 5). The radiance depends on the solar-phase angle in a way different from known laws of diffuse reflection, and the albedo is about

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the same as the lunar albedo (ref. 69). Variation of polarization with solar phase is similar to that of the Moon (ref. 29), although a recent interpretation of the polarization data suggests that Mercury may retain radiogenic argon (argon derived from decay of K^{40}) as part of a planetary atmosphere. There has been no direct evidence of the existence of an atmosphere. Surface markings on Mercury, although difficult to distinguish in any detail, appear to be similar to gross features of the Moon; that is, in apparent contrast, size, and distribution. Careful visual observation of the apparent motion of the surface features in 1950 showed that the period of rotation of Mercury is equal to its period of revolution around the Sun to better than 0.01 percent (ref. 9).

Infrared measurements show that the temperature of the center of the illuminated hemisphere of Mercury is 613° K at means solar distance (ref. 5). In 1961 microwave radiation (3.45 and 3.75 centimeters) from Mercury was measured. The brightness temperature for the entire disk was determined as 380° K (ref. 70). A knowledge of the temperature distribution on Mercury's disk is required to compare the microwave temperature with the earlier infrared temperature. The conventional assumption that the temperature is proportional to the fourth root of the solar-phase angle results in a computed temperature of 1100±300° K for the center of the sunlit hemisphere of Mercury at mean solar distance. This value can be matched with the infrared value only by assuming that the surface-temperature distribution is flatter; that is, cooler at the center of the sunlit hemisphere and somewhat warmer at the edges. This assumption is not unreasonable in view of the fact that photometric data indicate Mercury's surface to have reflection properties similar to those of the Moon.

Another source of information on Mercury became available in 1962, when radar echoes were obtained. The reflection coefficient appeared to be similar to that of the Moon (ref. 71).

chapter 3

Simulation and Terrestrial-Counterpart Studies

As THE TIME DRAWS NEARER when the Moon and closer planets will be explored by man, efforts to understand available data are intensified. In many laboratories, experiments have been performed to simulate extraterrestrial conditions and the effects they would have on materials likely to be on lunar or planetary surfaces. In many areas, geologists and mineralogists have conducted extensive field studies of rock formations and structures that are considered likely to have counterparts on extraterrestrial bodies.

There are obvious frustrations. In simulation and counterpart studies, the researcher finds himself forced to pile conjecture on conjecture and the validity of many assumptions and the number of undetected "rampant" variables are uncertain. However, even if the conclusions based on simulation and counterpart studies are not confirmed later by exploration, it is certain that the studies will clarify the direct observations when they are made.

HYPERVELOCITY IMPACTS AND SHOCK EFFECTS

The surface of the Moon (and quite likely that of Mercury) has been formed to a large extent by the impact of meteors. With no atmosphere to intercept even the smallest meteor, all sizes can strike the lunar surface with full velocity. After impact, the resulting crater is disturbed only by solar radiation and by impacts of later meteors and micrometeors. Because of the low value of the gravitational force (one-sixth that at the Earth's surface), the high velocity of impact, and lack of atmospheric braking action, the material ejected by the impact is scattered over a large area. (See, for example, the summary of lunar-ballistics data on pp. 36–43 of ref. 10.)

During the past 6 years many laboratory experiments have been performed on the mechanisms and products of hypervelocity impact (ref. 72). The investigations have covered the size and shape of craters, mass, size, and velocity distribution of secondary particles, and mineralogical and crystallographic changes induced in the impacted material. Experiments have been performed on small-scale models. Targets have varied from dense basalt to 70 percent porous pumice. Weakly bonded sand targets (43 to 47 percent porosity), both fine grained and coarse grained, have been tested. In a number of experiments, projectiles (mass $\lesssim 0.1$ gram) with velocities ≈ 6 km/sec were used (ref. 73). Crater-depth-to-diameter ratios varied from 1:5 for basalt to 1:1 for pumice. The amount of material displaced by a hypervelocity impact was found to be about the same as that displaced by a chemical explosive having the same TNT-equivalent energy as the kinetic energy of the projectile (corrected for angle of impact).

The two significant conclusions of these experiments with respect to lunar impact cratering were as follows. The flux of fragments of a given mass which are ejected from the lunar surface can be expected to be at least three and probably four orders of magnitude greater than the flux of the impacting particles of the same mass. Most of the ejected fragments will not escape from the lunar surface, but will fall back and produce secondary impact events (ref. 74). (These secondary particles could constitute a hazard to man and instruments on the Moon, although it seems likely that almost all the secondary particles will have relatively low energies.)

A consequence of these findings is that the lunar surface could consist of a mixed rubble of unsorted rock fragments (from large blocks to submicroscopic particles), including shock-produced glass, which have been abraded to finer size (by interplanetary particles and crater ejecta) and at least partially covered with a mantle of fine particles.

One important question is whether this picture holds for porous targets. Recent limited experimental data confirm that hypervelocity impact on porous targets (simulating postulated lunar-surface materials) also ejects an appreciable mass of fragmented debris from the impact crater (ref. 73). The results also imply that even micrometeorites would produce a cover of secondary fragments on the lunar surface. Hypervelocity impacts on a strong vesicular material similar to pumice were not as effective in producing secondary particles.

Another important aspect of meteoritic impact is the effect of the associated shock on the target material. It has been found, for example, that stishovite, a high-pressure form of quartz found in Meteor Crater (refs. 75 and 76), can be produced when sandstone or other quartz-bearing material is explosively shocked (pressures in the range 150 to 280 kilobars, temperatures 150° to 300° C). Other studies of "shock mineralogy," including research on the thermoluminescence of shock-produced minerals (see ref. 75) for identifying shock effects, have clarified the mineralogy of terrestrial meteoritic craters and craters caused by nuclear blasts. (See refs. 77 and 78.) If shock-transformed minerals are found on the lunar surface, they will constitute evidence of impact events, and their composition and distribution will provide data on the impact.

(The presence of shock-formed minerals in craters is a strong argument against volcanic origin.) Recently, an inexpensive technique for determining the shock equation of state of rock specimens has been developed at the U.S. Geological Survey (ref. 79).

It is well known that shock waves in a solid can result in sufficient local heating to cause luminescence. Investigations of the flash of light accompanying hypervelocity impacts in lunar-material research have suggested the possibility that under certain favorable conditions (unfortunately limited), impacts of space probes or of large meteors on the Moon might be detected by observing the associated impact flash (ref. 80).

VACUUM EFFECTS

The ultrahigh vacuum, $\sim 10^{-12}$ torr, existing on the Moon's surface has only recently been achieved on a routine basis in some laboratories. Experiments performed with fine powders (1 to 15 μ in diameter) of rock materials (olivine and obsidian) in ultrahigh vacuum showed definitely that the powders exhibit some adhesion. For example, 125-μ particles required an acceleration of 12 g to remove them from the substrate. Further experiments are in progress (ref. 81).

The results are significant in two respects: first, they imply that lunar-surface dust has some cohesiveness and hence some mechanical strength; second, they warn the space explorer that cold welding, as between moving spacecraft parts, may be a problem in lunar landings. (The astronaut may also find that lunar materials tend to stick to his equipment.) These initial experiments show there is still much to be learned about materials that have existed for long periods in ultrahigh vacuum.

RADIATION EFFECTS AND SPUTTERING

The environment of an "atmosphereless" satellite or planet is unusual in another respect: solar radiation (X-rays, ultraviolet radiation, and so forth), cosmic radiations, and particles (protons and alpha particles) from solar winds and storms continually bombard all materials on the surface of the satellite or planet. The high-energy X-rays and cosmic radiation penetrate the surface and cause darkening of rocks and minerals (ref. 82). The effects of lower energy particles (up to ~20 keV) of the solar wind and solar storms have been investigated during the past few years and have been found to cause the surface material to be eroded by sputtering. Extrapolating to lunar-surface materials exposed to a solar-wind flux (estimated from Explorer X, Mariner II, and Lunik II data) of 2×10^8 protons/cm²/sec (1.85-keV protons) and 0.3×10^8 alpha particles/cm²/sec (7.40-keV alpha particles), it has been estimated that in 4.5×10^9 years the Moon would lose about 20 centimeters from its surface (ref. 83). (The alpha particles do most of the damage.) Much of the sputtered material would be ejected with velocities greater than the lunar escape velocity (~2.2 km/sec). The combined effect of sputtering, meteoritic and micrometeoritic bombardment, and solar radiation absorption is a steady (but gentle compared with terrestrial processes) erosion of the lunar surface.

Besides being significant in lunar-erosion processes, sputtering also tends to clean the particles of the lunar-surface materials. This will increase adhesion between particles as they come into contact, and thereby help consolidate a lunar-dust layer. In experimental work, this effect has been manifested by the formation of a crust on bombarded powders.

THERMAL AND OPTICAL PROPERTIES

Many experiments have been performed on simulated lunar materials to determine optical and thermal properties. The purpose has been to find what materials have optical and thermal properties matching those of the lunar surface.

As mentioned earlier, two observed unique features of the lunar surface are the unusual photometric function (a high backscatter and an extremely low forward reflectivity) and the anomalous scattering function (independent of the angle between the scattering surface and either the direction of incident or direction of emergent light; the scattering does depend, however, on the angle between the incident light and the emergent light). A large number of terrestrial rock materials (basalt, sandstone, obsidian, pumice, and so forth) have been examined; none exhibits the anomalous photometric function (ref. 84). The best optical matching in the laboratory has been obtained with rock powders (ref. 85). Basically, the lunar-surface material should have a highly porous and open structure, cavities in the surface should be interconnected, and the scattering material must be dark and opaque with rough microsurfaces. With proper particle size ($\approx 10\,\mu$) and compaction (porosity $\approx$90 percent), the polarization can be made to match lunar observations. The depth of layer required to match the observed optical properties of the lunar surface need be only a few millimeters; however, the thermal properties of the lunar surface must also be matched.

One thermal property of the lunar surface that can be measured is the thermal inertia, a quantity determined by following (by infrared and microwave observation) the cooling of the lunar surface during lunar eclipses or at the beginning of a lunar night. Measured values of the "thermal inertia constant" (the reciprocal of the square root of the product of density, thermal conductivity, and specific heat) for the lunar-surface material may vary from 350 to more than 1000-cgs units. By comparison the value for solid rock is ~10; for pumice, ~100; for loose dust, ~1000 (ref. 86).

As the thermal-inertia constant involves three unknowns (which are temperature dependent), there is room for argument about each. Some planetologists agree, however, that the density of the lunar-surface material must be about 0.4 gm/cm^3, and if meteoritic and tektite data (discussed later) are relevant to lunar composition, the specific heat must be about 0.2 cal/gm/°C. If these two values are used with the thermal-inertia constant, it is possible to compute the thermal conductivity, and then use this last item in the experimental matching studies.

Unfortunately, the thermal-inertia constant determined from lunar observations does not have a single universally accepted value. Recently (ref. 87), the lunar "midnight" temperature was reevaluated to take account of the finding that there is significant emission by the Earth's atmosphere in the 8- to 14-μ infrared region (ref. 88), and found to be 102° K. This revised value makes the observed thermal-inertia constant about 750 cgs units. If this value is accepted, then from the previously assumed values of the density and specific heat of lunar-surface material, it follows that the thermal conductivity is 2.2×10^5 cal/cm/sec/°C, a value which can be matched, for example, by quartz powder in a vacuum. The density depends on how the material is laid down and whether sputtering and adhesion (cold welding) tend to compact the material. Some planetologists would argue for a higher value for the density (refs. 89 and 90).

From the above discussion it is obvious that matching optical and thermal properties does not lead to an unambiguous identification of the lunar-surface material. However, it does rule out a number of possibilities; specifically, almost all terrestrial rocks. But the matching process does not identify the chemical composition, nor does it give information on mechanical strength. The latter is of urgent interest to the astronaut. Optical matching does not eliminate the possibility of compaction or interparticle cohesion beneath the first few millimeters of surface material. In principle, thermal matching does place some limits, but the uncertainty in the density and, to a lesser extent, in the specific heat leaves leeway for appreciable cohesiveness.

Thus, extensive laboratory work to date in simulating the lunar surface leaves considerable room for debate. One cannot yet obtain, from observation of the optical and thermal properties of the Moon, reliable information on such important quantities as the bearing strength of the lunar surface or its chemical and mineralogical composition. Lunar probes, manned or unmanned, will be needed to secure more data.

TERRESTRIAL COUNTERPARTS OF LUNAR FEATURES

Ever since the invention of the telescope, the similarities between certain lunar and terrestrial features have been noted. Recently, studies of such "terrestrial counterparts" have been intensified. In particular, geologists in many countries have conducted aerial and field surveys of meteoritic craters. As an example, a study of Meteor Crater in Arizona, undertaken by the U.S. Geological Survey, will be described here. The study was augmented by an investigation of the crater formed in a near-surface detonation of a nuclear explosive.

Careful surveys and identification of the debris at Meteor Crater have clarified the events accompanying meteor impact. Comparison of the major structural features of Meteor Crater with those of craters formed in the alluvium of Yucca Flat (Nevada) by the Teapot Ess nuclear detonation (1.2-kiloton TNT-equivalent), in 1955, has revealed remarkable similarities. From the comparative studies, it has been possible to reconstruct the probable sequence of events that occurred during the formation of Meteor Crater. The following description is taken from the summarizing report (see ref. 76):

(1) The meteorite approaches the ground at 15 km/sec . . . enters the ground, compressing and fusing the rocks ahead and flattening them by compression and by lateral flow. The shock wave then reaches the rear of the meteorite.

(2) The rarefaction wave is reflected back through the meteorite, and the meteorite is decompressed but still moves at about 5 km/sec into the ground. Most of the energy has been transferred to the compressed, fused rock ahead of the meteorite.

(3) The compressed slug of fused rock and trailing meteorite are deflected laterally along the path of penetration. The meteorite becomes liner of transient cavity.

(4) The shock propagates away from the cavity, cavity expands, and fused and strongly shocked rock and meteoritic material are shot out in the moving mass behind the shock front.

(5) A shell of breccia with mixed fragments and dispersed fused rock and meteoritic material is formed around the cavity. The shock is reflected as a rarefaction wave from the surface of the ground and momentum is trapped in material above cavity.

(6) The shock and reflected rarefaction reach limit at which beds will be overturned. Material behind the rarefaction is thrown out along ballistic trajectories.

(7) Fragments thrown out of the crater maintain approximate relative positions except for material thrown to great height. Shell of breccia with mixed meteoritic material and fused rock is sheared out along walls of crater; upper part of mixed breccia is ejected.

(8) Fragments thrown out along low trajectories land and become stacked in an order inverted from the order in which they were ejected. Mixed breccia along the walls of the crater slumps back toward center of crater. Fragments thrown to great height shower down to form a layer of mixed debris.

Scaling from the Teapot Ess Crater indicates the energy released in the formation of Meteor Crater had a TNT-equivalent of 1.2 to 1.8 megatons, and that the release was about 100 meters below the original surface. The incident meteoritic mass was estimated as 63 000 to 166 000 tons.

In the initial stages of formation of Meteor Crater, the shock wave produced sufficiently high pressure and temperature conditions to transform some sandstone to lechatelierite, coesite, and stishovite. These shock-produced minerals have been found in the crater debris.

The study of Meteor Crater and Teapot Ess Crater described above, as well as studies by others (refs. 91 and 92), have increased substantially our understanding of the formation of craters by meteoritic impact. The findings are generally consistent with the results of laboratory experiments on hypervelocity impact.

There have been fewer space-related studies of volcanic craters, a reflection of the belief that much is known of them already. In addition, many agree—although there are some who take the opposite point of view—that the present topography of the lunar surface is more likely a consequence of meteoritic impact than of volcanic activity.

chapter 4

Lunar and Planetary Chemical-Mineralogical Composition and Genesis

EVIDENCE OF GROWING INTEREST in the solar system is seen in the increased research on meteorities and tektites and in more extensive studies of the origin of the solar system. Most of the work has deep roots in earlier research, and the significant achievements of the last 6 years are not readily identified.

STUDIES OF METEORITES

The origin of meteorites is still a subject for active discussion. There is a consensus that no single sequence of events can account for their origin, particularly because of the many kinds of meteorites. About 93 percent of the observed falls are stony meteorites (density 3.0 to 3.9 gm/cm^3); the remainder are irons (7.8 gm/cm^3) and stony irons (4.6 to 4.9 gm/cm^3). (See ref. 93.) The stones are subdivided into chondrites and achondrites. The former are distinguishable from the latter in that they contain "chondrules," which are spheres or spheroids ($\approx$3 millimeters or more in diameter) of silicates or other minerals.

During the past 6 years, research on meteorites has exploited many of the recently developed analytical techniques, ranging from electron microscopy to mass spectrometry and neutron-activation analysis (ref. 94). Substantial effort has gone into the use of radioactivity dating methods (ref. 95), which may enable the life history of some meteorites to be determined. The interval between the time of breakup of the meteorite parent body and the time of fall, assuming the meteor is exposed to interplanetary radiation during this interval, is determined by measuring the cosmic-ray-induced radioactivity (H^3, Cl^{36}, Ar^{39}). If the time of fall is not known, a lower limit to the time the meteorite has resided on Earth can be established by determining the decay of the cosmic-ray-induced radioactivity. Some time after its formation, the meteorite parent body may have melted and chemical fractionation (e.g., partial separation of metal and silicate phases) resulted; these processes can be dated by measuring certain long-lived radioactivities and stable end products (Rb^{87}, Sr^{87}, U^{235}, etc.). Other techniques of radioisotope and stable-isotope analysis may be used to estimate the preatmospheric sizes of certain meteorites.

It is still not possible to fit the accumulating data into one or more consistent theories of meteoritic genesis. A few researchers hold the view that some meteors originated in the Moon. Others believe that they originated in a single generation of asteroid-sized bodies. Harrison Brown has expressed the feelings of some planetologists rather well (ref. 96):

> At one time I thought that I understood meteorites. However, I made the mistake of experimenting, and it seems that the more experiments I have performed the more confused I have become. . . . One clear fact emerges—that is we are not dealing with any one body . . . we may well be dealing with a multiplicity of origins.

In any event, the accumulation of a large amount of meteorite data during the past 6 years represents an achievement, even if the data cannot yet be fitted into consistent and satisfying patterns.

STUDIES OF TEKTITES

Research on tektites has been greatly stimulated during the past 6 years. Tektites may be the only pieces of the Moon in terrestrial laboratories for some time. Recently, age determinations (K^{40}/Ar^{40} method) for the four recognized tektite-strewn fields have shown (ref. 97) the Indo-Australian tektites to be the youngest (0.72×10^6 years), followed by those of the Ivory Coast (1.3×10^6 years), Europe (14.6×10^6 years), and America (34×10^6 years). The spread in age values indicates that tektite showers are rare.

In view of the relatively small spread in properties (density from 2.30 g/cm^3 to 2.58 g/cm^3; refractive index, 1.48 to 1.51; SiO_2 content, 68 percent to 78 percent; Al_2O_3 content, 9.5 to 16.5 percent; water content, 0.02 percent; and ferric/ferrous ratio, ≈ 0.05), it seems probable that, unlike the meteorites, there is only one mechanism of origin for tektites (ref. 98). There are only 4 recognized tektite-strewn fields, while, in contrast, more than 1600 areas have contained meteorites (ref. 99). Even the tektite masses are relatively uniform; only a few are bigger than 1 kilogram, a few hundred are between 0.5 and 1.0 kilogram, and the rest ($>10^6$) are all less than 0.5 kilogram.

The evidence accumulated during the past 6 years is heavily weighted in favor of lunar origin. Apparently the tektites were derived from the Moon by the impact of large meteorites. The impact melted siliceous igneous rock, with volatilization of some of the alkalis, and ejected fragments at ≈ 3 km/sec from the lunar surface (ref. 100). The various "strewn fields" are of such large extent (hundreds of square miles) that terrestial origin is questionable; moreover, no crater seems to be associated with any of the strewn fields. The low ferric iron content also sug-

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gests that tektites were not formed in the oxidizing conditions of the Earth's atmosphere. The fact that the Fe/Ni/Co ratio of tektites is very similar to that in many terrestrial materials (in contrast to the ratio for meteorites) leads some to favor terrestrial origin. In addition, the Pb/U/Th ratio is similar to that of some Earth sediments (ref. 101).

Studies of the button- and lens-shaped Indo-Australian tektites reveal ablation and melting structures consistent with transit through the Earth's amosphere, and indicate both velocities and trajectories such that the tektites probably came from an extraterrestrial source not far outside the Earth's orbit. In laboratory aerodynamic experiments (ref. 102), this mechanism has been verified. Recent research on the presence of minor elements (e.g., Mo, As, Ir) also supports an extraterrestrial origin.

If the tektites are derived from the lunar surface, then they are extremely valuable to the lunar geologist. As noted earlier, powdered siliceous materials match the observed optical and thermal properties of the lunar surface layer.

One planetologist has proposed (ref. 103) that the lunar-surface composition is like that of the "Igast object," an extraterrestrial high-silicate (not glassy) object that fell at Igast, Estonia, in 1864. Two persons witnessed the fall. The unusual feature of the Igast object is that a substantial part was not melted by passage through the atmosphere. Its SiO_2 and Al_2O_3 content is very similar to that of tektites.

chapter 5

Observations From Spacecraft

AMONG THE SIGNIFICANT ACHIEVEMENTS in planetology research during the past 6 years, the most spectacular are the several space flights in which planetology data were obtained. Although the total accumulation of planetology data from space probes is not large, it is important.

LUNIK II AND LUNIK III

On September 14, 1959, the U.S.S.R. interplanetary rocket Lunik II relayed back information on the lunar magnetic field. It was found that at one lunar radius from the Moon's surface, there were no indications of an external magnetic field with a general intensity of from 20 to 30 γ (1 $\gamma = 10^{-5}$ gauss). (Because, in the absence of lunar atmosphere, the solar wind tends to cancel the observed magnetic field about the sunlit surface, this result does not rule out the possibility of a field ≤ 0.01 gauss at the lunar surface.) Magnetometer observations above the dark surface of the Moon are desirable. (See p. 64 of ref. 78.) The data were interpreted as meaning that the effective magnetic moment of the Moon is not more than about 0.01 percent of the Earth's magnetic moment.

On October 7, 1959, Lunik III passed around the back of the Moon at 65 000 kilometers from the lunar surface (refs. 104–111). Photographs were taken during the 40 minutes while the vehicle was near the Moon-Sun line.

Unfortunately, in this position the lunar shadows were minimum, thereby reducing lunar-surface contrast. Several days later, when the orbit of Lunik III took it closer to Earth, the negatives were scanned by "a bright beam moving over the images, the number of lines reaching one thousand." Two scanning speeds were used: a slow scan at a greater distance from the Earth, and a more rapid scan when Lunik III was nearer. Each negative was transmitted several times.

An *Atlas of the Other Side of the Moon* was published in 1961 (ref. 109). Analysis of the photographs shows the same types of features as on the visible side—craters, maria, rays, mountains. However, greatly extended maria, such as Mare Imbrium and Mare Serenitatis, are absent. The photographs also indicate that at full Moon there is no darkening of the lunar limb; this implies that the microstructure of the far side is the same as that of the visible face of the Moon.

MARINER II

The U.S. space probe Mariner II was launched August 27, 1962, and on December 14, 1962, it passed about 34 800 kilometers (21 600 miles) from Venus' surface (fig. 1), at which time a series of measurements were made (ref. 112) for about 35 minutes. The spacecraft carried a magnetometer, an infrared radiometer capable of recording radiation from Venus at wavelengths of 8.4 and 10.4 μ, and a microwave radiometer capable of recording 13.5- and 19-millimeter radiation (fig. 2).

The magnetometer recorded no rise in the magnetic field above that of interplanetary space; fluctuations near Venus were smaller than the 5-γ lower limit of the changes observed in interplanetary space. This means that there is no Venusian magnetic field greater than 5 gammas at 40,000 kilometers from the planet's center on its sunward side. There could be a weak magnetic field confined to

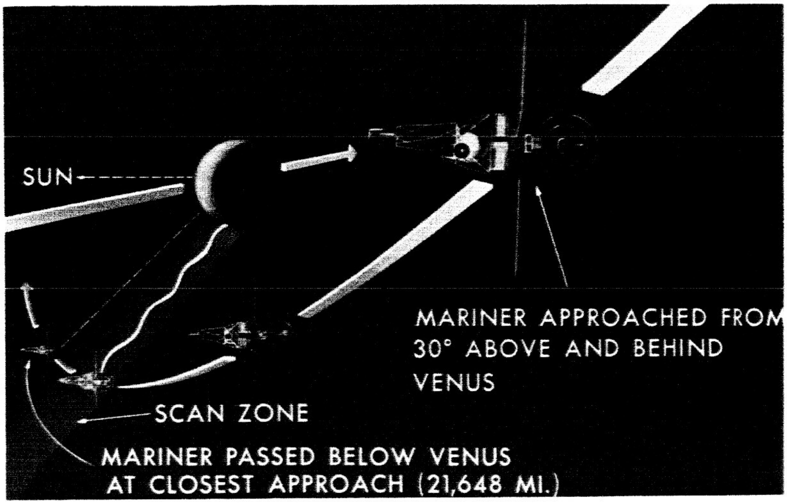

Figure 1.—Mariner II's pass of Venus as seen from Earth.

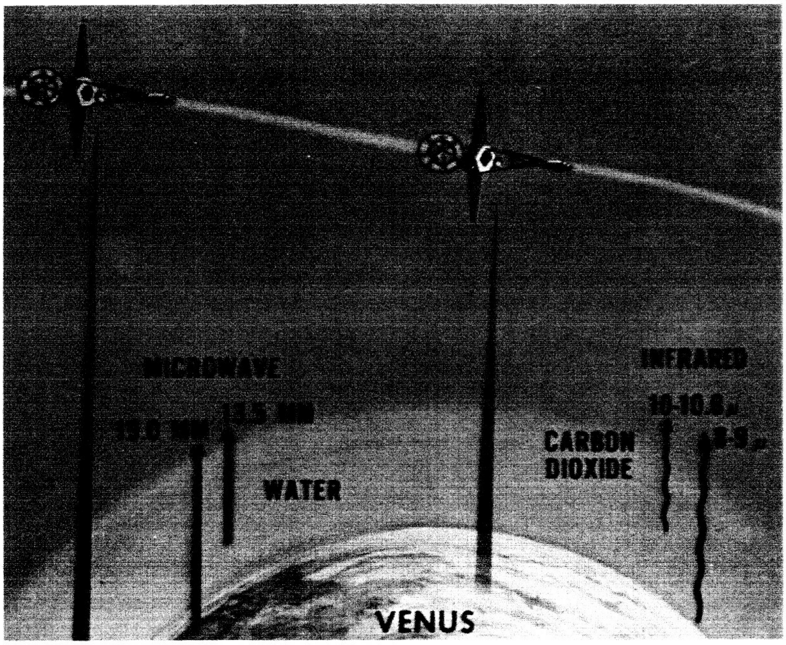

Figure 2.—Mariner II's radiometric experiments.

a region close to the sunward side. Comparison of the Mariner II data and the Pioneer V measurements near the Earth indicates that the magnetic dipole moment of Venus, if it is close to the Sun-Venus line, is less than 5 to 10 percent of the Earth's moment.

The finding of little or no magnetic field tends to confirm radio observations of a slow rotation rate for Venus. It also means that Venus does not experience the deflecting effect of a magnetic field on interplanetary charged-particle fluxes; the cosmic-ray flux may be the same in the equatorial regions of Venus as at its poles.

During flyby, 18 readings of the microwave (13.5- and 19-millimeter) radiation from Venus were made; 5 readings were made on the sunlit hemisphere, 5 on the dark hemisphere, and 8 across the terminator line (fig. 3). The 13.5-millimeter wavelength corresponds to a water absorption band; the 19-millimeter wavelength was not affected by water vapor. Thus, the larger the energy difference between the two radiometer readings at these two wavelengths, the greater the amount of water vapor in the planetary atmosphere. The temperature measurements gave a value of 415° C for the average surface temperature. The temperature on either side of the terminator was lower, indicative of a limb-darkening effect (the microwave radiation comes from the surface through a large thickness of atmosphere at the limb, and there is no high-electron-density atmosphere to alter this effect). There was not any significant phase (solar) effect for the 19-millimeter radiation, implying strong lateral (circumferential) convective mixing in the atmosphere.

The infrared measurements (8.4 and 10.4 μ) were made in the same way. The 10.4-μ radiation is absorbed by CO_2. Both wavelengths gave the same temperature, indicating that both came from the same depth in the Venusian atmosphere. The limb darkening was slight for the 10.4-μ radiation and somewhat stronger for the 8.4-μ radiation, suggesting a small concentration of CO_2 in the upper levels of the Venusian atmosphere. Temperatures in the cloud layer were the same on the sunlit and dark sides. The estimated temperatures were —35° C for the middle layer of clouds, as observed in the central portion of the planetary disk; —50° C at the upper cloud levels, as seen toward the limb; and 90° C for the cloud base, estimated to be 70 kilometers above the planet's surface. (The top of the clouds is thought to be about 100 kilometers above

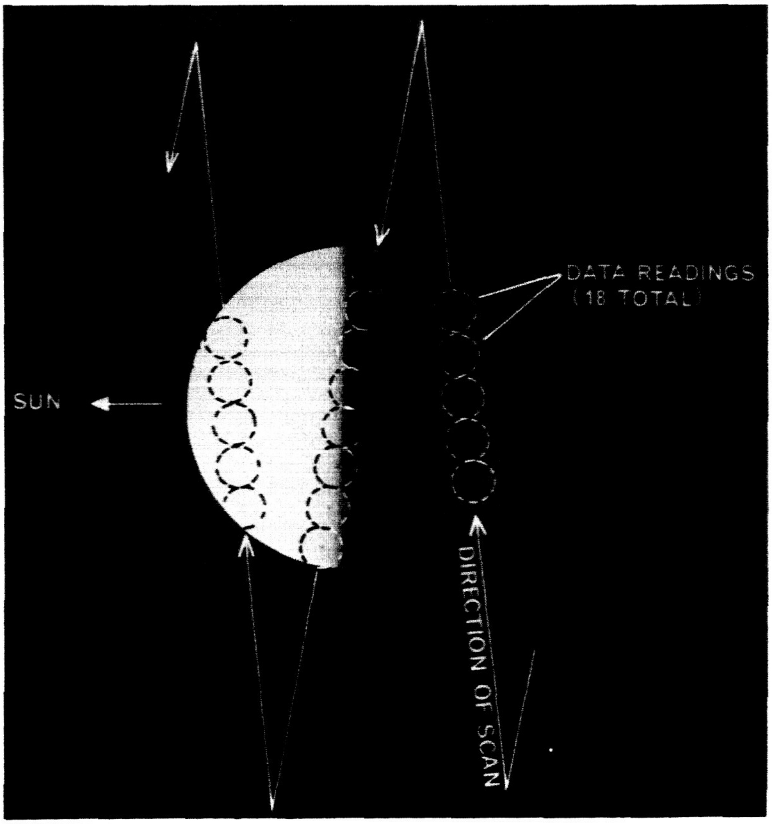

Figure 3.—**Paths of Mariner II's 18 radiometric scans of Venus.**

the surface.) A cold spot about 10° C colder than the remainder of the cloud layer was detected near the southern end of the terminator. This was also observed in simultaneous, Earth-based infrared surveys of Venus (ref. 113). This cold spot is perhaps associated with some hidden surface feature.

Radio tracking of Mariner II during its flyby provided a more accurate value of the mass of Venus: 0.81485±0.015 percent of the Earth's mass.

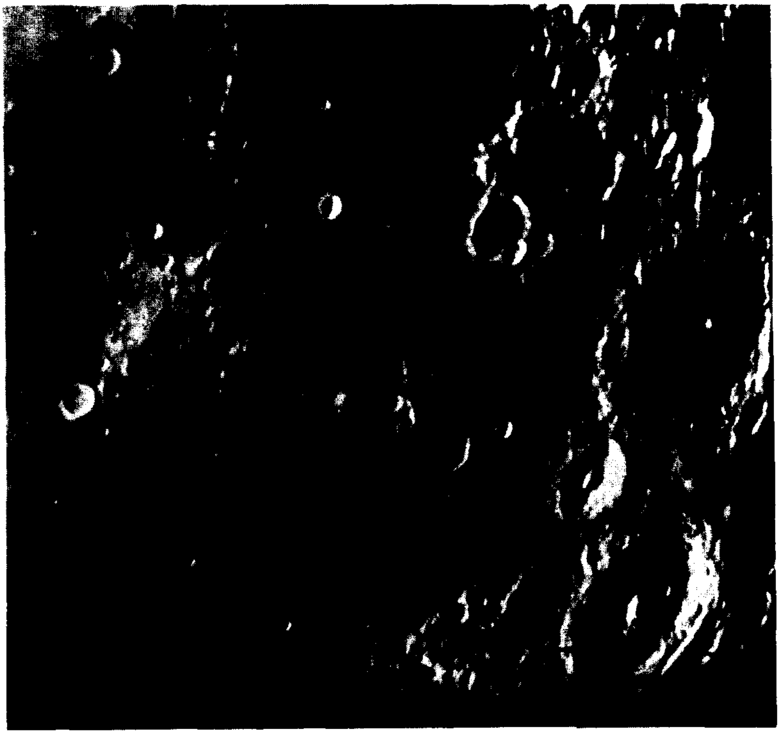

Figure 4.—Views of craters Arzachel (bottom right), Alphonsus (center right), and Guericke (upper left) taken by Ranger VII from an altitude of 1163 miles above lunar surface.

RANGER VII

On July 31, 1964, the U.S. spacecraft Ranger VII was directed to collide with the Moon in the neighborhood of Mare Cognitum (ref. 114). During the last 17 minutes of almost vertical descent to the lunar surface, 6 TV cameras (two wide-angle and four narrow-angle) took

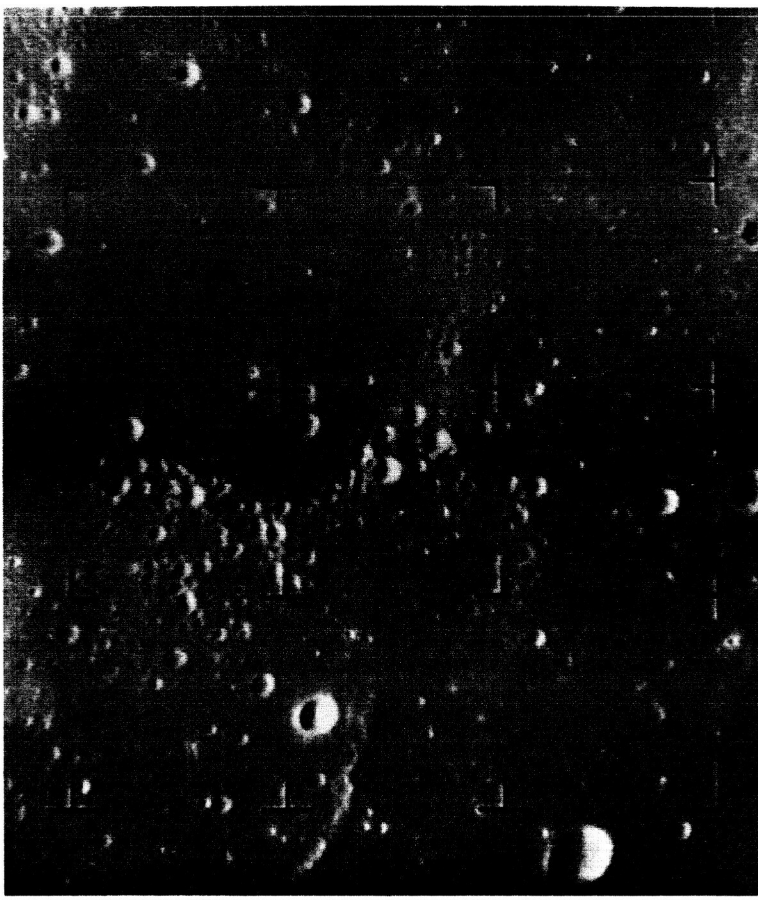

Figure 5.—**A swarm of large Eratosthenian secondary lunar craters, photographed from an altitude of 44.8 miles.**

4316 high-resolution photographs and transmitted them back to Earth (figs. 4–6). The wide-angle cameras had focal-plane shutters and took one picture every 2.56 seconds with a 1/200-second exposure. The narrow-angle camera had focal-plane shutters and took one picture every 0.2 second with a 1/500-second exposure. Different aperture settings on the cameras assured proper exposure. The last full-scan photograph was taken 2.3 seconds before impact, from an altitude of 3 miles (5 kilometers) (fig. 7); a partial photograph was obtained from an elevation of about 300 meters.

The photographs obtained were of excellent quality and revealed a large amount of detail on the lunar surface.

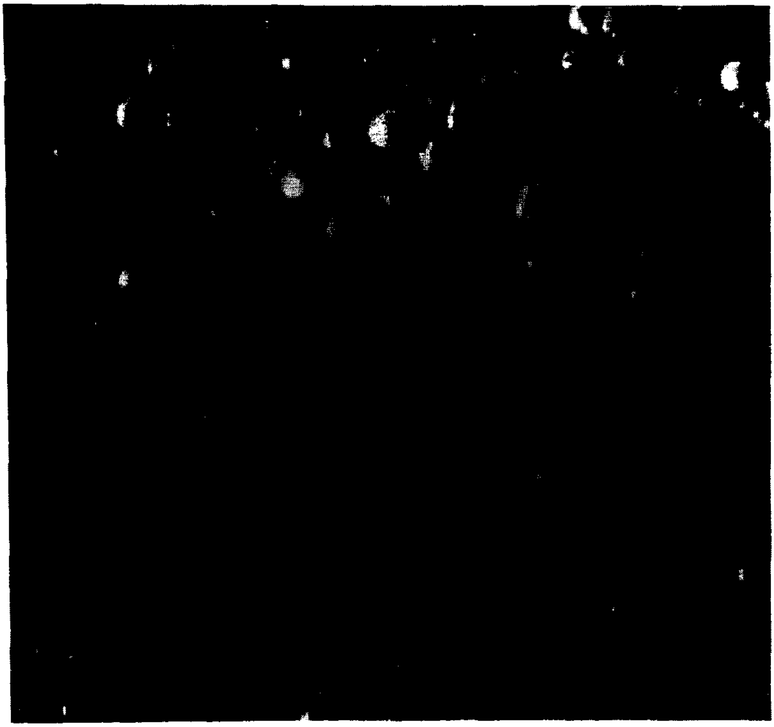

Figure 6.—Ranger VII photograph of lunar craters—presumably secondaries of Tycho—with a maximum diameter of 1 kilometer.

They showed it to be smooth within the mare. There were many scattered craters as small as a few meters in diameter, but correspondingly shallow. An atlas of the photographs is being published (ref. 115). The consensus of those who have examined the photographs is that, from a topographical point of view, the target area would be suitable for a lunar landing.

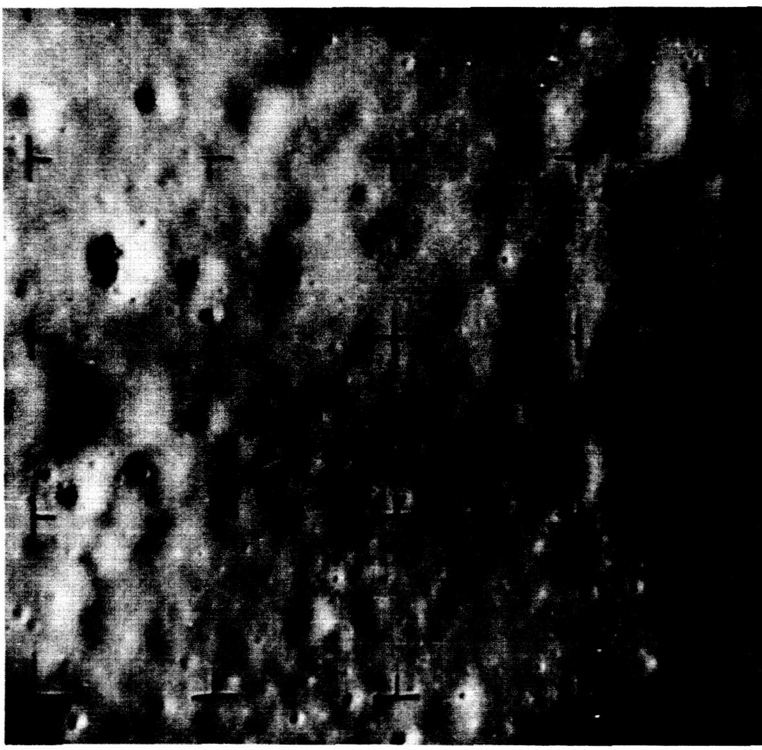

Figure 7.—The last "A" camera photograph of elongated secondary craters in a Tycho ray, taken from an altitude of about 3 miles, before Ranger VII hit the Moon. The picture shows a crater with internal rock masses, depressions, and dimple craters as small as 30 feet in diameter and 10 feet deep.

chapter 6

Instrumentation for Planetology Research

IMPORTANT ACHIEVEMENTS during the past 6 years have been the development and, in a few cases, use of instruments in lunar and planetary space probes. Ground-based instrumentation has also received considerable attention, and, for example, new infrared detectors and radio telescopes have been developed and put to good use. The latest technology has been exploited: television techniques have been used in optical telescopes; computers have been applied to data analysis; and all Earth-based work has shared in the widespread general advances in analytical and optical apparatus.

In this report, only the unique instrumentation associated with planetology research is considered, that is, the space-vehicle instruments.

The instrumentation is intended to provide information on the chemical and mineralogical composition and the physical properties of lunar and planetary surfaces; information on the subsurface structures (anomalies, layering, base rock, etc.) of the planets and the Moon; and information on composition of planetary atmospheres. Some instruments are designed for flyby probes, others for orbiters, and others for soft- and hard-landing vehicles. Most of the instruments initially developed are for remotely controlled, self-operating devices. Instrumentation for astronaut operation is also under development.

The environment of space requires that instrument design emphasize (ref. 116): small size, light weight, minimum power consumption, shock and vibration resistance, operation in high vacuum without release of material that might impair operation of other instruments, reliability, and remote operation. For exploratory missions the instruments must have wide dynamic range (usually with some sacrifice in accuracy and stability), and for missions where the limits of measurement are certain, the instrumentation should emphasize accuracy and stability and, if possible, provide for in-flight calibration. The shorter missions (lunar) require operation during about 1 to 3 weeks; longer (planetary) missions require operation during 6 months or more.

Some idea of the magnitude of the achievements during the past 6 years can be obtained by noting the characteristics of the instruments used on Mariner II in the exploration of Venus. The scientific instrumentation weighed only 22.1 kilograms and required 21.9 watts to operate. Yet there were eight components: microwave radiometer with scan actuator, infrared radiometer, solar-plasma instrument magnetometer, cosmic-dust collector, particle-flux detector, ion chamber, and data conditioner with power switching. This instrumentation fed signals to the data-transmission system. Mariner II was launched August 27, 1962, and the instrumentation operated properly for at least 130 days.

The achievement in instrumentation represented by the Ranger VII photographic mission is impressive—a total of 4316 high-resolution pictures of the lunar surface, sent a quarter-million miles from six TV cameras in a compact, space-hardened subsystem weighing 173 kilograms.

A seismometer and a γ-ray spectrometer were sent on early Ranger probes; unfortunately, the flights were not successful. However, some inflight γ-ray data were acquired.

A number of other instruments have been developed for remote analysis or sensing of lunar and planetary surfaces (some can also be used in lunar or planetary orbiters).

These include gravity meter, mass spectrometer, X-ray diffractometer, X-ray spectrometer, neutron-activation detector, and alpha- and gamma-backscatter devices.

Infrared spectrometry is very promising as a remote-analysis technique. In support of the instrumentation development, a catalog of over 5000 infrared spectra of various rocks and minerals has been assembled (ref. 117).

In view of the great difficulties involved in developing instrumentation for space probes, it might be useful to consider here what advantages are obtained by making measurements closer to the lunar or planetary objects. Earlier, it was pointed out that, under the best geometrical conditions, Venus has an angular diameter, when viewed from Earth, of only 64 seconds. When Venus was viewed from Mariner II during the flyby, the angular diameter was about 17°. This is more than 1000 times larger than the angle observed at Earth. (To Mariner II, Venus appeared about 35 times larger in the sky than the Moon appears to an observer on Earth.) The radiation received from any specific area of the sunlit hemisphere of Venus is increased by a factor of more than 10^6 in intensity by moving the measuring instrument from the Earth's surface to the Mariner II flyby position.

chapter 7

Summary and Conclusions

MOON

THE LUNAR SURFACE has undoubtedly been examined more carefully during the last 6 years than ever before. A lunar atlas has been published, and detailed maps have been made at a scale of 1:1 000 000 over the range of ±32° of the Equator. Photometric studies have enabled the preparation of so-called geological maps of a portion of this area. Visual changes in color have been observed near the crater Aristarchus, and unusual luminescence has been reported around the region of the crater Kepler. Temperature measurements of the cooling rate of the lunar surface after sundown and during an eclipse have shown that many areas cool at a much slower rate than others. These are often associated with craters, but in some instances are mare areas. Radar measurements of the lunar surface have been made in the range from 68 centimeters to 4 millimeters. These show an increasing degree of diffuse reflection with decreasing wavelengths. It has not yet been possible to compute the dielectric constant of the lunar surface, although some calculations indicate that it is approximately 2.5. Laboratory measurements of the reflection characteristics of many materials lead to the conclusion that the lunar surface is composed of "spongy" material. Proton bombardment of geological materials has shown darkening presumably similar to the effect of the solar wind on the lunar surface.

Photographs taken with the Ranger VII spacecraft show that craters are the dominant topographic features on the

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Moon. Craters less than 300 meters in diameter cannot be classified by shape alone in the categories previously adopted for telescopic observation. In the area comprising Mare Cognitum, craters larger than 1 meter in diameter occupy about 50 percent of the surface. Often, smaller craters are superimposed on larger craters. A slope-distribution curve has been made, using a base length of 1 meter. This shows that the median slope is about 5°. About 90 percent of the slopes are less than 16° and 10 percent are less than 1°.

There is a further need for studies of other areas of the lunar surface by larger spacecraft and by the Lunar Orbiter spacecraft. Also, astronomers have been encouraged to make extensive observations of the crater areas, particularly Aristarchus, for further evidence of short-term changes such as red clouds. Use of radar techniques can improve our knowledge of the characteristics of the lunar surface over areas not accessible to landed spacecraft. Chemical and physical analyses of the lunar surface, such as can be accomplished by Surveyor and later Apollo spacecraft, are necessary for an understanding of the origin and history of the Moon. Many selenodetic observations of value with respect to characteristics of the Moon can be made by the Lunar Orbiter.

VENUS

The rotation rate of Venus has been determined to be 248 days, with a retrograde motion. Mariner II data showed that the magnetic field of Venus was less than one-tenth that of the Earth. No evidence was obtained for any radiation belts. The microwave radiometer showed no significant difference in temperature between the sunlit and dark sides of Venus. Extrapolated temperature measurements indicate a high surface temperature, perhaps as much as 500° C. One small area was observed to be at a lower temperature than the rest of the surface (some 10° C), which was confirmed by ground-based observations at greater resolution than was available from the spacecraft.

Advances in this discipline concerning Venus will require extended radar studies, and ultimately orbiting and landing spacecraft, to measure characteristics of the planet.

MARS

Observations of the radio emissions of Mars have shown that there are no electrical storms comparable to those observed on the Earth. Radar measurements have been attempted, but inconclusive results have been obtained. The large radar telescopes are now planning further studies of Mars, and useful results are anticipated. Many additional photographs of the planet have been taken, and a Planetary Information Center has been established at the Lowell Observatory to assemble all photographs of Mars and other planets for use by investigators in this field. The atmospheric pressure remains in great doubt, and much additional spectroscopic work is needed.

Mariner IV is designed to photograph Mars through red and green filters at a distance somewhat less than 6000 nautical miles. This should increase our knowledge of the surface characteristics of that planet by a factor of 100, at least in a band some 200 miles wide across the surface.

Additional information will be obtained through the use of orbiting and landing capsules in the Voyager program.

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U.S. GOVERNMENT PRINTING OFFICE : 1966 O—208-481